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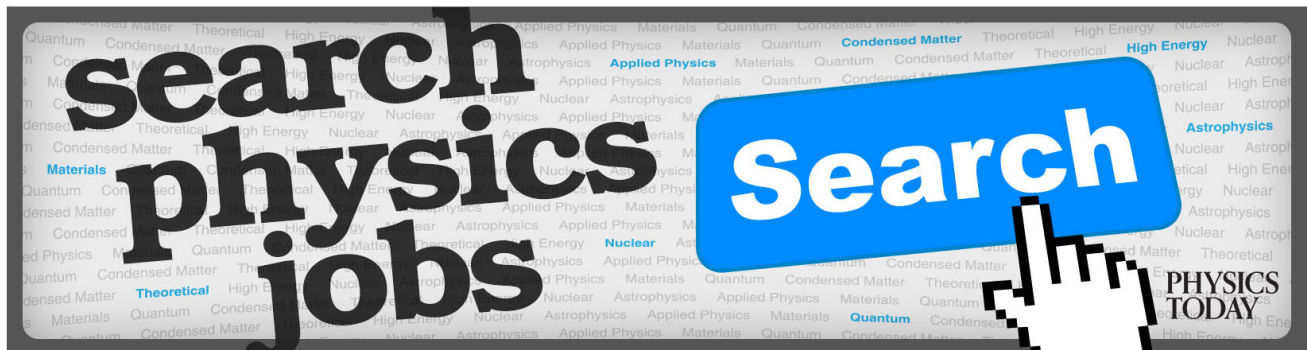
Effect of magnetic islands on the localization of kinetic Alfvén wave

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Recent studies have revealed an intimate link between magnetic reconnection and turbulence. Observations show that kinetic Alfvén waves (KAWs) play a very crucial role in magnetic reconnection and have been a topic of interest from decades in the context of turbulence and particle heating. In the present paper, we study the role that KAW plays in the formation of coherent structures/current sheets when KAW is propagating in the pre-existing fully developed chain of magnetic islands. We derived the dynamical equation of KAW in the presence of chain of magnetic islands and solved it using numerical simulations well as analytic tools. Due to pre-existing chain of magnetic islands, KAW splits into coherent structures and the scale size of these structures along transverse directions (with respect to background magnetic field) comes out to be either less than or greater than ion gyro radius. Therefore, the present work may be the first step towards understanding how magnetic reconnection generated islands may affect the KAW localization and eventually contribute to magnetic turbulence. In this way the present approach may be helpful to understand the interplay between magnetic reconnection and turbulence in ion diffusion region. © 2015 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4936873]

I. INTRODUCTION

Space is an infinite laboratory to study various plasma phenomena and is accessible to detailed *in-situ* measurements. Magnetic reconnection is a universal phenomenon in astrophysical, space, and laboratory/fusion plasmas, and has been studied in different space regions, for example, the magnetosphere,[1–6] solar wind,[7,8] etc. Turbulence is ubiquitous in space plasma and is known to play a very crucial role as it cascades energy from large to small scales, eventually leading to dissipation and particle heating. Earth's magnetosphere is often very turbulent, with considerable evidence of Alfvénic fluctuation.[9–12]

The two processes, turbulence and reconnection, are known to be connected to each other.[13] Karimabadi and Lazarian[14] have reviewed the effects of turbulence on the reconnection rate, i.e., how pre-existing turbulence modifies Sweet-Parker reconnection and how turbulence may develop because of reconnection. Experiments with forced turbulence suggest that turbulent reconnection is faster than laminar reconnection system and reconnection rate increases with increasing turbulence level.[15,16] Since most of the space plasmas are turbulent in nature, pre-existing turbulence must be taken into account while studying magnetic reconnection and vice-versa, i.e., preexisting magnetic reconnection can affect the turbulence. Also, magnetic reconnection itself induces turbulence that feeds back to magnetic reconnection. Though there appears to be a close relationship between turbulence and reconnection and it is known that turbulence affects reconnection, the physics of their interplay is still not very clear. Recently, Xu *et al.*[17] have reported solar wind reconnection using dual-spacecraft observations and identified the corresponding Alfvénic electron outflow jet, derived from decouple between ions and electrons, which show direct evidence for kinetic effects that dominate the reconnection. They also concluded that the turbulence associated with the solar wind reconnection exhaust is a kind of background solar wind turbulence, which implies that the reconnection generated turbulence, has not developed much. But for the purpose of understanding the interplay between turbulence and reconnection, it is important to study the role that reconnection plays explicitly in generating turbulence, even though weak, which has been carried out in the present paper.

In the presence of a guide magnetic field, the dynamics in reconnection diffusion regions may be described in terms of generalized kinetic Alfvén waves (KAWs). In the past, analysis exploiting the multipoint observations from the Cluster spacecraft as they passed through a reconnection diffusion region showed that KAWs play a very crucial role in magnetic reconnection in Earth's magnetosphere.[18] Nonlinear/dispersive properties of KAW in high beta plasmas have received a great deal of research interest from decades in the context of turbulence and particle heating. This study becomes even more important when the turbulence and reconnection are affecting each other. It has also been found that the turbulence leads to the emergence of coherent structures. These coherent structures can be in the form of current sheets/filaments having scale size varying from ion scales to electron scales. The importance of current sheets/coherent structures in the dissipation range of the solar wind turbulence where dissipation might be arising through magnetic reconnection or some other processes has been reported in previous literature.[19] Particle-in-cell simulations reveal that, when the current layers that form during magnetic reconnection become too intense, they disintegrate and spread into a complex web of filaments that can further lead to turbulence which can be measured with satellite.[20]

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Tearing mode is a very common instability in magnetized plasmas. Tearing mode leads to the formation of magnetic islands. Cluster observations have detected the presence of magnetic islands near a reconnection site in the magnetotail.[21–23] Using 2D particle in-cell (PIC) simulations, it has been showed that fast reconnection is realized by the excitation of tearing instabilities that generate magnetic islands.[24] An ion inertial length-scale magnetic island is observed to be attached to the electron current sheet (ECS), separating it from another reconnection layers by Cluster spacecraft.[25] These magnetic islands are also considered as a site for generation of energetic electrons.[22] The physical mechanism behind generation of these energetic electron or particle acceleration is not yet well understood.

The analysis done by Chaston *et al.*[18] shows that KAWs play an important role in magnetic reconnection and it has been reported in literature that nonlinearity associated with KAW contributes in an important way towards the generation of turbulence. Also, turbulence is associated with the generation of coherent structures. Therefore, magnetic reconnection may affect the formation of localized structures. In view of the above scenario, we present a model where KAW is propagating in the pre-existing magnetic reconnection site. The present work aims to understand how magnetic islands generated due to reconnection may affect KAW localization and eventually contribute towards magnetic turbulence. Similarly, the present study may be helpful in understanding the interplay between magnetic reconnection and turbulence. Along with this, the proposed mechanism can also be useful in understanding the physics behind the generation of high energy electrons from magnetic island sites. Present study is carried out for the low power KAW only in order to develop a basic understanding of how the KAW localization and formation of current sheets of sub proton scales takes place by the pre-existing fully developed chain of magnetic islands. It should be mentioned here that a high power KAW may generate the turbulence because of nonlinear effects as discussed in the literature.[26–29] In that case, it would be difficult to study the isolated effect of reconnection induced turbulence as investigated in the present work. The organization of the paper is as follows: Section II involves the model equations for the KAW followed by the numerical simulation. In Section III, we present a semi-analytical model in order to understand the physics of the formation of localized structures and Section IV comprises summary and conclusion.

II. MODEL EQUATIONS

A. Kinetic Alfvén wave

Dynamical equation of three dimensionally propagating KAW is derived having wave vector $\vec{k}_0 = k_{0x}\hat{x} + k_{0y}\hat{y} + k_{0z}\hat{z}$ and background magnetic field $\vec{B}_0$ is assumed to be along the z-axis. It is assumed that the fluctuations parallel to the magnetic field are negligible compared to $\vec{B}_0$. Magnetic field and electric field are connected with scalar and vector potentials by following relations $\vec{B}_\perp = \hat{z} \times \vec{\nabla}\tilde{A}_z$ and $\vec{E} = -\vec{\nabla}\phi - \frac{1}{c}\frac{\partial \vec{A}_z}{\partial t}$.

The equation of motion, continuity equation, Ampere's law, and Faraday's law are written as below:

$$\frac{\partial \vec{v}_j}{\partial t} = \frac{q_j}{m_j}\vec{E} + \frac{q_j}{c\,m_j}\left(\vec{v}_j \times \vec{B}\right) - \frac{k_B T_j}{m_j}\frac{\vec{\nabla}n_j}{n_0}, \tag{1}$$

$$\frac{\partial n_j}{\partial t} + n_j\vec{\nabla}.(\vec{v}_j) = 0, \tag{2}$$

$$\vec{\nabla} \times \vec{B} = \frac{4\pi}{c}\vec{J} + \frac{1}{c}\frac{\partial \vec{E}}{\partial t}, \tag{3}$$

$$\vec{\nabla} \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}. \tag{4}$$

Here, index j = e or i corresponds to the electrons and ions, respectively, k_B is the Boltzmann constant, n_0 is the background number density. v_j is the velocity, n_j is the number density, and T_j, m_j are the temperature and mass of species j. Making use of the same set of equations (1)–(4), using Ampere's law in parallel component of electron equation of motion and neglecting electron inertia we obtain the following equation for the scalar potential ϕ expressed as[26]

$$c\frac{\partial^2 \phi}{\partial t \partial z} + \frac{\partial^2 \tilde{A}_z}{\partial t^2} + c^2\lambda_{De}^2\frac{\partial^2 \nabla_\perp^2 \tilde{A}_z}{\partial z^2} = 0. \tag{5}$$

Writing the above equation in terms of vector potential $\tilde{A}_z$, we eliminated the scalar potential ϕ using ion dynamics, i.e., the perpendicular component of ion equation of motion with finite ion temperature and the continuity equation, and obtained the following form for the vector potential of KAW:

$$\left[\frac{\partial^2}{\partial t^2} + c^2\lambda_{De}^2\frac{\partial^2 \nabla_\perp^2}{\partial z^2} - \lambda_i^2\left(\frac{\partial^2}{\partial t^2} + \omega_{ci}^2\right)\frac{\partial^2}{\partial z^2}\right]\tilde{A}_z = 0. \tag{6}$$

Here, $\lambda_{De} = \left(\frac{k_B T_e}{4\pi n_0 e^2}\right)^{1/2}$ is the electron Debye radius, $\lambda_i = \left(\sqrt{c^2 m_i/4\pi n_0 e^2}\right)$ is the collision less ion skin depth. It gives the following dispersion relation for KAW:

$$\omega^2 = \frac{k_z^2 v_A^2 \left(1 + k_\perp^2 \rho_s^2\right)}{1 + k_z^2 \lambda_i^2}. \tag{7}$$

Here, ρ_s is ion gyroradius defined as $\rho_s = \frac{c_s}{\omega_{ci}}$.

If we take the field perturbation into account due to pre-existing chain of magnetic islands, then the dynamical equation for KAW upon neglecting higher order terms will take the following form:

$$\left[\frac{\partial^2}{\partial t^2} + v_A^2 \rho_s^2\frac{\partial^2 \nabla_\perp^2}{\partial z^2} - \lambda_i^2\frac{\partial^2}{\partial z^2}\frac{\partial^2}{\partial t^2} - v_A^2\left(1 + \frac{2\delta B}{B_0}\right)\frac{\partial^2}{\partial z^2}\right]\tilde{A}_Z = 0. \tag{8}$$

Here, B_0 is the background static magnetic field and δB is the perturbation in field due to the presence of magnetic islands. Using the relation of vector potential and magnetic field, we can re-write Equation (8) as follows:

$$\left[\frac{\partial^2}{\partial t^2} + v_A^2 \rho_s^2 \frac{\partial^2 \nabla_\perp^2}{\partial z^2} - \lambda_i^2 \frac{\partial^2}{\partial z^2}\frac{\partial^2}{\partial t^2} - v_A^2\left(1 + \frac{2\delta A_z}{A_0}\right)\frac{\partial^2}{\partial z^2}\right]\tilde{A}_z = 0.$$

(9)

Here,

$$\frac{\delta B}{B_0} = \frac{\delta A_z}{A_0}.$$

(10)

The solution for $\tilde{A}_z$ is written as $\tilde{A}_z = A_z(x,y,z)e^{-i(\omega_0 t - k_{0z}z)}$ where $A_z(x,y,z)$ is slowly varying in z compared to $\exp(ik_{0z}z)$. Substituting this solution in the dynamical equation for KAW under steady state and assuming $\partial_z A_z \ll k_{0z}A_z$, we get the following equation:

$$\frac{2i}{k_{0z}}\left(\frac{1 + k_\perp^2 \rho_s^2}{1 + k_{0z}^2 \lambda_i^2}\right)\frac{\partial A_z}{\partial z} + \rho_s^2\left(\frac{\partial^2 A_z}{\partial x^2} + \frac{\partial^2 A_z}{\partial y^2}\right) - \frac{2\delta A_z}{A_0}A_z = 0.$$

(11)

Writing the above equation in dimensionless form, we get

$$\frac{\partial A_z}{\partial z} + \left(\frac{\partial^2 A_z}{\partial x^2} + \frac{\partial^2 A_z}{\partial y^2}\right) - 2(\delta A_z)A_z = 0,$$

(12)

where normalizing parameters are $x_n = y_n = \rho_s$, $z_n = \frac{2}{k_{0z}}\left(\frac{1 + k_\perp^2 \rho_s^2}{1 + k_{0z}^2 \lambda_i^2}\right)$, $A_{zn} = A_0$

The profile for field fluctuations can be written as[30]

$$\delta A_z = A_0(-x^2/2 + \cos(b_0 y))$$

(13)

and

$$\delta A_z/A_0 = (-x^2/2 + \cos(b_0 y)).$$

(14)

Using relation (14), we can write Equation (12) as follows:

$$\frac{\partial A_z}{\partial z} + \left(\frac{\partial^2 A_z}{\partial x^2} + \frac{\partial^2 A_z}{\partial y^2}\right) - 2(-x^2/2 + \cos(b_0 y))A_z = 0. \quad (15)$$

We have numerically analyzed the spatial evolution of KAW pertinent to earth magneto tail. Using the magneto-tail parameters[18] and using $\omega_0 \approx 0.6\omega_{ci}$ and $k_{0x}\rho_s \approx 0.5$, the corresponding wave number is $k_{0x} = 1.79 \times 10^{-8} \text{cm}^{-1}$ and $k_{0z} = 6.2 \times 10^{-7}\text{cm}^{-1}$. The values of the normalizing parameters are $z_n = 3.2 \times 10^8$ cm, $x_n = y_n = 2.8 \times 10^7$ cm.

B. Numerical simulation

We numerically solved Equation (15) in a two dimensional periodic spatial domain of size $2\pi/\alpha_x \times 2\pi/\alpha_y$ with 256×256 grid points and $\alpha_x = \alpha_y = 0.1$. We applied pseudo spectral method for space integration in x-y plane and a finite difference method along with a predictor corrector scheme for spatial evolution along z direction with a step size $\Delta z = 10^{-5}$. The initial profile of KAW has been taken as $A_z(x,y,0) = A_0$. Here $|A_0| = 1$ is the initial amplitude of KAW. Before solving our present equation, we determined accuracy of the code by checking the conservation of Plasmon number, $N = \sum_k |A_{zk}|^2$ for well-known nonlinear Schrödinger equation. The Plasmon number was found to remain constant with an accuracy of 10^{-6} during our computation. The code was then customized for solving Equation (15).

The spatial evolution of A_z is studied by changing the parameter b_0. Figure 1 illustrates the spatial distribution of A_z in (i) x-z plane and (ii) y-z plane for different values of b_0. Due to the presence of pre-existing chain of magnetic islands, the localization of wave takes place giving rise to coherent structures of different intensity and size at different locations. The presence of these coherent structures indicates the generation of turbulence in the site of chain of magnetic islands. Also, the figures clearly depict that the amplitude of
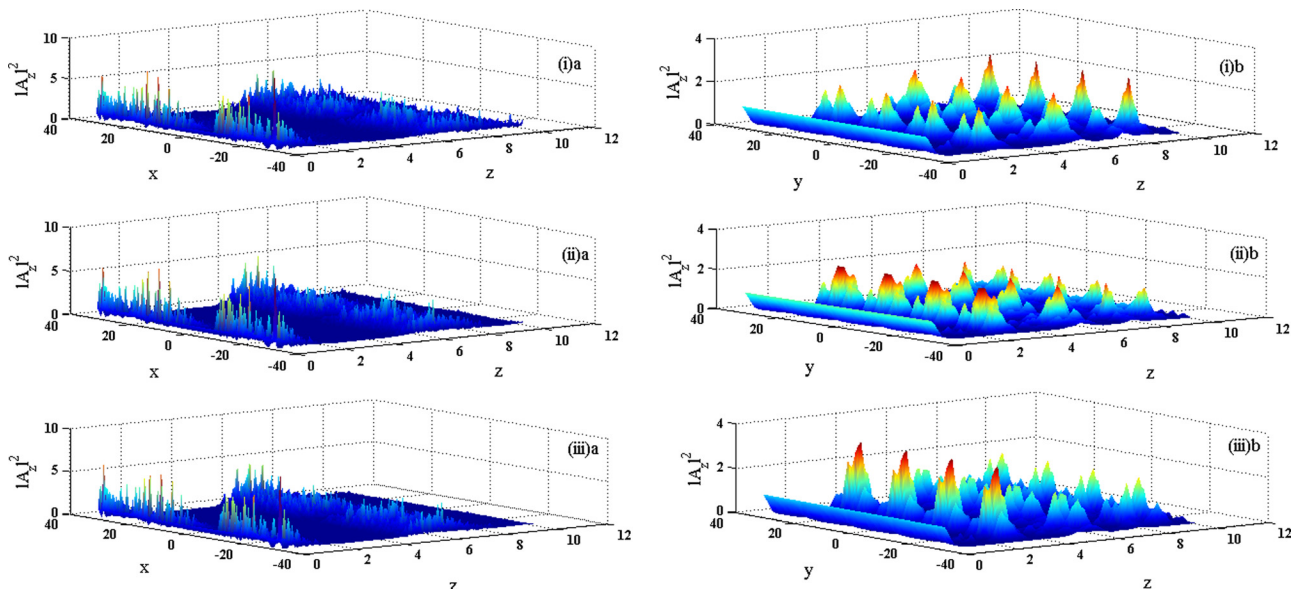

FIG. 1. The spatial variation of A_z in (a) x-z plane and (b) y-z plane obtained by numerical simulation for three different values of b_0: (i) $b_0 = 0.5$, (ii) $b_0 = 0.7$, and (iii) $b_0 = 0.8$.
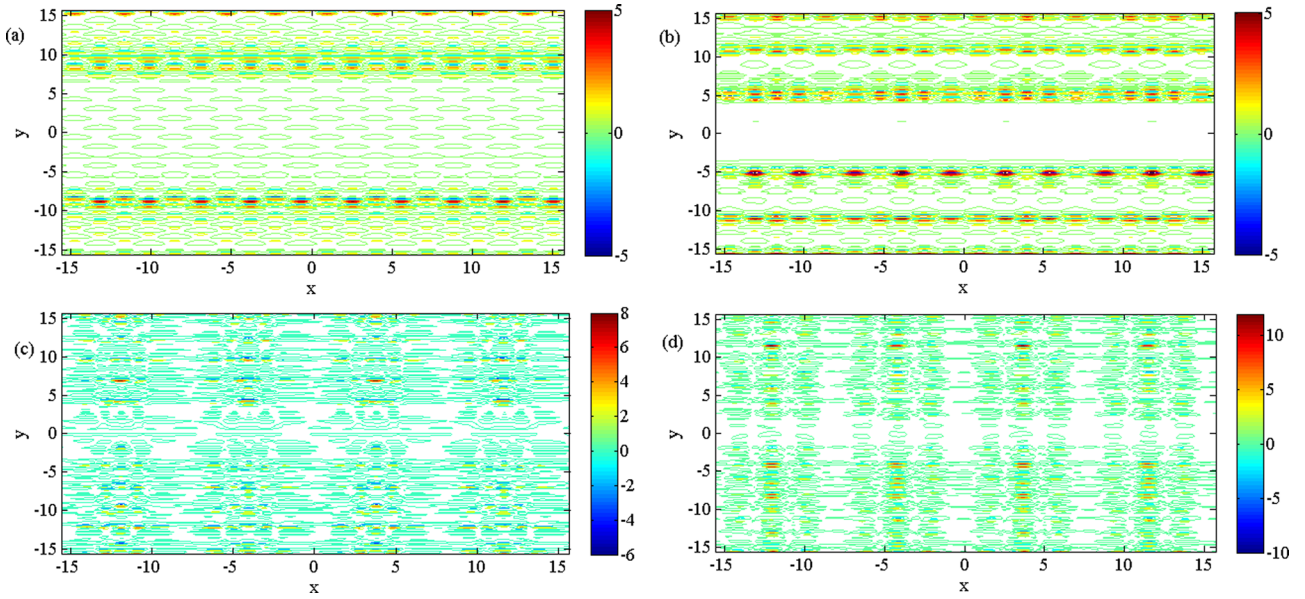
FIG. 2. Plot of current density in x-y plane at different values of z: (a) z = 2, (b) z = 4, (c) z = 10, and (d) z = 15.

these coherent structures depends directly upon the strength of b_0. Along x axis, the characteristic scale size of these coherent structures formed in the present case comes out to be of the order less than ρ_s, which is the typical island width in the current case and scale size along y axis is greater than ρ_s. This should be mentioned here that for the simulation parameters taken here, the grid size in transverse directions (along x and y directions) is of the order of $0.1\,\rho_s$ which is adequate enough to resolve scale sizes observed here. This indicates that the present approach can be helpful to understand the interplay between magnetic reconnection and turbulence in ion diffusion region. The asymmetric behaviour of A_z along x and y directions, as expected, can be seen from Figure 1. To have insight of the formation of coherent structures and the asymmetric behaviour along the x and y directions, we also developed a semi-analytical model as discussed in Section III.

Further, in order to have insight of the evolution of magnetic flux which is related to current density function by Ampere's law, we next study the spatial evolution of current

density function by performing simulation of Equation (14) with the typical initial condition[31] $A_z(x, y, 0) = \cos(2x + 2.3) + \cos(y + 4.1)$. Figures 2(a)–2(d) display plot of current density in x-y plane at z = 2, 4, 10, 15, respectively. The figure depicts that current sheets of the order of sub proton scales are formed. One can see that in the initial state, current is having smooth distribution which at larger z becomes unstable and results into irregular structures.

III. SEMI-ANALYTICAL METHOD

In the present section, we solved the dynamical equation of KAW represented by Equation (11) semi-analytically[32] within the paraxial regime by assuming the solution as

$$A_z = A_{z0}(x, y, z)e^{ik_{0z}s(x,y,z)}. \tag{16}$$

By substituting this solution in Equation (11) and separating the real and imaginary part, we obtain

$$2A_{z0}\left(\frac{1 + k_\perp^2 \rho_s^2}{1 + k_{0z}^2 \lambda_i^2}\right)\frac{\partial s}{\partial z} + \rho_s^2 k_{0z}^2 A_{z0}\left(\left(\frac{\partial s}{\partial x}\right)^2 + \left(\frac{\partial s}{\partial y}\right)^2\right) - \rho_s^2\left(\frac{\partial^2 A_{z0}}{\partial x^2} + \frac{\partial^2 A_{z0}}{\partial y^2}\right) + \left(x^2 - 2\cos(b_0 y)\right)A_{z0} = 0, \tag{17}$$

$$\frac{2}{k_{0z}}\left(\frac{1 + k_\perp^2 \rho_s^2}{1 + k_{0z}^2 \lambda_i^2}\right)\frac{\partial A_{z0}}{\partial z} + 2\rho_s^2 k_{0z}\left(\frac{\partial A_{z0}}{\partial x}\frac{\partial s}{\partial x} + \frac{\partial A_{z0}}{\partial y}\frac{\partial s}{\partial y}\right) + \rho_s^2 k_{0z}A_{z0}\left(\frac{\partial^2 s}{\partial x^2} + \frac{\partial^2 s}{\partial y^2}\right) = 0. \tag{18}$$

Solutions of Equations (17) and (18) for an initial Gaussian beam can be written as follows:

$$A_{z0}^2 = \frac{A_{00}^2}{f_1 f_2}e^{\left(-\frac{x^2}{r_{01}^2 f_1} - \frac{y^2}{r_{02}^2 f_2}\right)}, \tag{19}$$

$$S = \beta_1(z)\frac{x^2}{2} + \beta_2(z)\frac{y^2}{2} + \phi(z), \tag{20}$$

$$\beta_1 = \frac{1}{\rho_s^2 k_{0z}^2}\left(\frac{1 + k_\perp^2 \rho_s^2}{1 + k_{0z}^2 \lambda_i^2}\right)\frac{1}{f_1}\frac{df_1}{dz}, \tag{21}$$
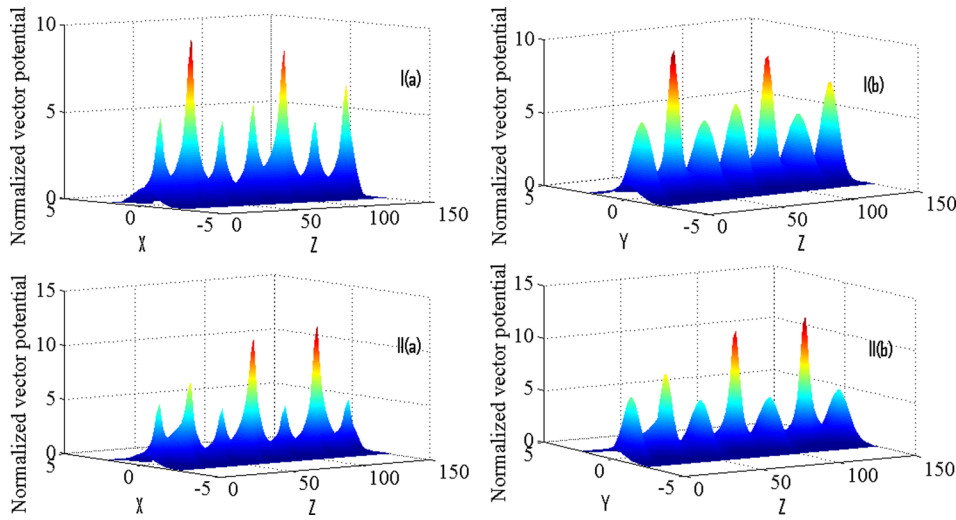
FIG. 3. The distribution of vector potential of KAW in (a) x-z plane and (b) y-z plane obtained semi-analytically for two values of b_0: (i) $b_0 = 0.5$ and (ii) $b_0 = 0.8$.

$$\beta_1 = \frac{1}{\rho_s^2 k_{0z}^2}\left(\frac{1 + k_\perp^2 \rho_s^2}{1 + k_{0z}^2 \lambda_i^2}\right)\frac{1}{f_2}\frac{df_2}{dz}, \qquad (22)$$

where r_{01} and r_{02} are the transverse scale sizes, β_1 and β_2 are slowly varying function of z, and f_1, f_2 are the beam width parameters of wave. Using Equations (19)–(22) in Equation (17) along with the paraxial approximation (i.e., $x \ll r_{01}f_1$, $y \ll r_{02}f_2$), and equating the coefficient of x^2 and y^2 on both sides, we obtain the equation for dimensionless beam width parameters f_1 and f_2, respectively, as

$$\frac{d^2 f_1}{d\xi^2} = R_d^2 k_{0z}^2 \left(\frac{1 + k_{0z}^2 \lambda_i^2}{1 + k_\perp^2 \rho_s^2}\right)^2 \left(\frac{\rho_s^4}{f_1^3 r_{01}^4} - f_1\right), \qquad (23)$$

$$\frac{d^2 f_2}{d\xi^2} = R_d^2 k_{0z}^2 \left(\frac{1 + k_{0z}^2 \lambda_i^2}{1 + k_\perp^2 \rho_s^2}\right)^2 \left(\frac{\rho_s^4}{f_2^3 r_{02}^4} - b_0 f_2\right), \qquad (24)$$

where $R_d = k_{0z} r_{01}^2$ and $\xi = z/R_d$. For the set of parameters stated above with $r_{01} = 5.99 \times 10^7\,\mathrm{cm}$, $r_{02} = 6.99 \times 10^7\,\mathrm{cm}$, Equations (23) and (24) are solved for plane wavefront with the initial conditions as $\frac{df_1}{dz} = \frac{df_2}{dz} = 0$ at z = 0; and $f_1 = f_2 = 1$ at z = 0. KAW propagating through the chain of magnetic islands experiences a converging force and diverging force. The first term in the above equations account for the diverging term and second term is the due to pre-existing islands. When the converging effect dominates over diverging force, KAW gets localized. But these converging and diverging effects are different along the x and y directions leading to the difference in localization for f_1 and f_2. The scale size can be calculated by comparing the diverging and converging term in Equations (23) and (24). It is seen that the scale size along x-axis comes out to be of the order of ion gyro radius, i.e., $r_{01} \approx \rho_s$; and the scale size along y-axis is of the order of, $r_{02} \approx \rho_s/b_0$. Since the value of b_0 is always less than unity, which implies the scale size along y-axis is greater than ion gyroradius. This provides a clue about the applicability of the model in understanding the interplay between magnetic reconnection and turbulence in the ion diffusion region. Figure 3 shows the

localization for 3D KAW in (a) x-z plane and (b) y-z plane obtained semi-analytically at two different values of b_0. By changing the value of b_0 the magnitude of the normalized vector potential of KAW is found to be affected and these results are consistent with simulation.

IV. SUMMARY AND CONCLUSION

This paper focuses on the study of kinetic Alfvén wave properties and formation of coherent structures and current sheets of sub proton scales by the pre-existing fully developed chain of magnetic islands. Due to separate ion and electron scale physics, the diffusion region where magnetic field and plasma decouple from each other has two scale structures, viz., the ion scale and electron scale. Multipoint observations from the Cluster spacecraft reveal that KAWs are important in facilitating magnetic reconnection.[18] We derived dynamical equation for KAW in the presence of pre-existing fully developed chain of magnetic islands. Numerical simulation shows that the KAW propagating in the pre-existence of islands gets localized and formation of coherent structures takes place which indicates the generation of turbulence. Also, turbulence can lead to generation of reconnecting current sheets. Results show the formation of current sheets of sub proton scales is found for the same case. This signifies that the KAW propagating in the presence of fully developed chain of magnetic islands may provide a useful mechanism to understand the interplay between magnetic reconnection and turbulence in ion diffusion region. The proposed mechanism can also be useful in understanding the physics behind the generation of high energy electrons from the site of magnetic islands.

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